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Supersymmetric Hints from Precision Electroweak Data?

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Abstract

The Standard Model does not provide a very good fit to the most recent precision electroweak data from LEP, due primarily to the observed branching ratios for Z decay to $b\bar{b}$ and $c\bar{c}$. The possibility that an extension of the Standard Model with low-energy supersymmetry can improve the agreement between data and theory is considered.

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The Standard Model does not provide a very good fit to the most recent precision electroweak data from LEP, due primarily to the observed branching ratios for Z decay to $b\bar{b}$ and $c\bar{c}$. The possibility that an extension of the Standard Model with low-energy supersymmetry can improve the agreement between data and theory is considered.

1 The R_b–R_c–α_s crisis

Experiments at LEP and SLC measure more than fifteen separate electroweak observables in Z decay events. A global fit to these observables exhibits a remarkable consistency with Standard Model (SM) expectations, with two notable exceptions. Defining $R_Q \equiv \Gamma(Z \to Q\overline{Q})/\Gamma(Z \to \text{hadrons})$, with $Q = b, c$, the LEP Electroweak Working Group global fit yields[1]

$$R_b = \begin{cases} 0.2219 \pm 0.0017, & \text{LEP/SLC global fit;} \\ 0.2156, & \text{SM prediction,} \end{cases} \qquad (1)$$

which is a 3.7σ discrepancy, and

$$R_c = \begin{cases} 0.1543 \pm 0.0074, & \text{LEP/SLC global fit;} \\ 0.1724, & \text{SM prediction,} \end{cases} \qquad (2)$$

which is a 2.5σ discrepancy. Because the measurements of R_b and R_c are highly correlated, it is useful to examine the contours of $\Delta\chi^2$ in the R_b–R_c plane with respect to the best fit to the observed data.[2] When this is done, one finds that the Standard Model prediction lies just outside the 99.9% contour. Taken at face value, this would suggest that the probability that the Standard Model describes the data is less than one in a thousand!

One other LEP measurement relevant to this discussion is the $\alpha_s(m_Z)$ determination from the total hadronic width of the Z. Based on the measurement of $R_\ell \equiv \Gamma_{\rm had}/\Gamma_{\ell\ell}$, Ref. 1 finds $\alpha_s(m_Z) = 0.126 \pm 0.005 \pm 0.002$ (where the last error quoted corresponds to varying the Higgs mass from 60 GeV to 1 TeV). The LEP determination of $\alpha_s(m_Z)$ tends to be somewhat higher than the extrapolated value of $\alpha_s(m_Z)$ obtained from lower energy measurements. In a recent review for the Particle Data group, Hinchliffe quotes[3] extrapolated values of $\alpha_s(m_Z) = 0.112 \pm 0.005$ from low-energy deep inelastic scattering data and $\alpha_s(m_Z) = 0.115 \pm 0.003$ from a lattice QCD determination based on bottomonium spectroscopy. Shifman has argued eloquently [4] that the tendency of lower values of $\alpha_s(m_Z)$ determined from low-energy observables as compared to the higher values of $\alpha_s(m_Z)$ measured at LEP presents a serious discrepancy that could be a signal of new physics beyond the Standard Model.

There may be a connection between the $\alpha_s(m_Z)$ "discrepancy" and the R_b and R_c measurements.[5] If new electroweak physics contributes positively [negatively] to $\Gamma_{\rm had}$, then the QCD contribution to $\Gamma_{\rm had}$ determined from LEP data must be reduced [increased], since the sum is fixed by the observed data. Consequently, the value of $\alpha_s(m_Z)$ determined at LEP from $\Gamma_{\rm had}$ would have to be reduced [increased]. Thus, better agreement between the value of $\alpha_s(m_Z)$ as determined from $\Gamma_{\rm had}$ and lower energy data could be achieved if there exists a positive contribution of new physics to $\Gamma_{\rm had}$.

The required magnitude of the new contribution can be determined as follows. Let $\Gamma^{(0)}_{\rm had}$ be the tree-level decay rate for $Z \to$ hadrons in the Standard Model, and let $\alpha_s^{(0)}$ be the value of $\alpha_s(m_Z)$ extracted from LEP data based on the measured value of $Z \to$ hadrons under the SM hypothesis. If there is a non-SM electroweak component to $\Gamma_{\rm had}$, denoted below by $\delta\Gamma_{\rm new}$, then the true value of α_s should be determined (in the approximation where QCD effects are treated at one-loop) by

$$\Gamma_{\rm had} = \Gamma^{(0)}_{\rm had}\left(1 + \frac{\alpha_s^{(0)}}{\pi}\right) = \Gamma^{(0)}_{\rm had}\left(1 + \frac{\alpha_s}{\pi}\right) + \delta\Gamma_{\rm new}\,. \quad (3)$$

As an example, suppose that new electroweak physics contributes only to R_b, and not to R_c or R_q (where q is a light quark flavor). Then,

$$\Gamma_{b\bar{b}} = \Gamma^{(0)}_{b\bar{b}}\left(1 + \frac{\alpha_s^{(0)}}{\pi}\right) = \Gamma^{(0)}_{b\bar{b}}\left(1 + \frac{\alpha_s}{\pi}\right) + \delta\Gamma_{\rm new}\,, \quad (4)$$

where $\Gamma^{(0)}_{b\bar{b}}$ is the SM tree-level decay rate for $Z \to b\bar{b}$. Note that by assumption, $\delta\Gamma_{\rm new}$ is the same quantity in eqs. (3) and (4). Let $R_b^{\rm SM} = \Gamma^{(0)}_{b\bar{b}}/\Gamma^{(0)}_{\rm had}$ be the predicted

value of R_b in the Standard Model (note that the dependence on α_s drops out in the ratio at one-loop). Then,

$$R_b = \frac{\Gamma_{b\bar{b}}}{\Gamma_{\rm had}} = \frac{\Gamma^{(0)}_{b\bar{b}}(1+\alpha_s/\pi)+\delta\Gamma_{\rm new}}{\Gamma^{(0)}_{\rm had}(1+\alpha_s/\pi)+\delta\Gamma_{\rm new}}\,. \tag{5}$$

Inserting $\Gamma^{(0)}_{b\bar{b}} = R_b^{\rm SM}\Gamma^{(0)}_{\rm had}$ in eq. (5), and eliminating $\delta\Gamma_{\rm new}$ using eq. (3), all factors of $\Gamma^{(0)}_{\rm had}$ drop out and one can solve for α_s. The result is:

$$\frac{\alpha_s(m_Z)}{\pi} = \left(\frac{1-R_b}{1-R_b^{\rm SM}}\right)\left(\frac{\alpha_s^{(0)}(m_Z)}{\pi}\right) - \frac{R_b-R_b^{\rm SM}}{1-R_b^{\rm SM}}, \tag{6}$$

As an exercise, let us insert $R_b = 0.2219$, $R_b^{\rm SM} = 0.2156$, and $\alpha_s^{(0)} = 0.126$. Using eq. (6), we would then find $\alpha_s(m_Z) = 0.100$, which is somewhat lower than any of the values of $\alpha_s(m_Z)$ quoted above.

In the above example, I assumed that there was no new physics contribution to R_c. Nevertheless, one should still expect a slight shift from the SM prediction, $R_c^{\rm SM} = \Gamma^{(0)}_{c\bar{c}}/\Gamma^{(0)}_{\rm had}$. Following similar steps as above,

$$R_c = \frac{\Gamma_{c\bar{c}}}{\Gamma_{\rm had}} = R_c^{\rm SM}\left(\frac{1+\alpha_s/\pi}{1+\alpha_s^{(0)}/\pi}\right)\,, \tag{7}$$

from which it follows that:

$$R_c = R_c^{\rm SM}\left(\frac{1-R_b}{1-R_b^{\rm SM}}\right)\,. \tag{8}$$

Using the same numbers as before with $R_c^{\rm SM} = 0.172$, one would predict $R_c = 0.171$.

One can consider other scenarios. For example, if new physics contributes only to R_c, then the above formulae can be used by interchanging b and c everywhere. For $R_c = 0.1543$, one would find $R_b = 0.2202$. Unfortunately, the value of α_s obtained is $\alpha_s(m_Z) = 0.196$, which is completely inconsistent with other measurements.

One must be very careful in interpreting the observed R_b and R_c discrepancies from Standard Model expectations. The experimental procedures that identify b and c quarks in Z decays are difficult and prone to large systematic errors. Regarding the R_c measurement, note that the quoted error is larger, and the statistical significance of the deviation from the Standard Model prediction is smaller than those of R_b. Moreover, the experimentally observed value for $R_b + R_c$ is *lower* than the corresponding SM prediction. Hence, if new physics contributes only to R_b and R_c, then the QCD contribution to $\Gamma_{\rm had}$ must be *larger* than its value in the Standard Model, implying a value of $\alpha_s(m_Z)$ that is too large. Of course, this statement implicitly assumes that there are no new physics contributions to R_q where q is a light quark. However, there is no known source of new physics that can modify R_q sufficiently to compensate the deficit in $R_b + R_c$ to avoid the above conclusion. Thus, I am inclined to discount the measured value of R_c above, and assume that its true value is close to the Standard Model expectation.

Should one discount the measured value of R_b as well? Further experimental analysis is required to clarify the situation. However, as argued earlier, if R_b is the only source of new physics, then the value of $\alpha_s(m_Z)$ deduced from $\Gamma_{\rm had}$ will be lower than its SM-determined value, and potentially in better agreement with the extrapolation from lower energy data. Furthermore, R_b is the most sensitive (among the partial Z-decay rates) to new physics. This is due, in part, to the large Higgs-top quark Yukawa coupling, which generates a significant one-loop correction to R_b.

Henceforth, I shall assume that R_c is given by its Standard Model prediction. In the experimental determination of R_b, there is some contamination of $c\bar{c}$ events in the $b\bar{b}$ sample that must be subtracted. This subtraction depends on the value of R_c assumed. Fixing R_c to its Standard Model value, a slightly smaller value of R_b is found by the Electroweak working group compared to the value quoted above:[1]

$$R_b = 0.2205 \pm 0.0016, \qquad \text{LEP/SLC global fit,} \tag{9}$$

roughly a three standard deviation discrepancy from the Standard Model prediction.

For completeness, I note here that the $Zb\bar{b}$ vertex corrections can also affect the left-right $b\bar{b}$ asymmetry, $\mathcal{A}_b \equiv (g_L^2 - g_R^2)/(g_L^2 + g_R^2)$, where g_L (g_R) are the couplings of the left (right) handed bottom quarks to the Z. The corrections to R_b and $\mathcal{A}_b$ can be parameterized as a function of the corrections to the left– and right–handed bottom quark vertices,[6]

$$\frac{\delta\mathcal{A}_b}{\mathcal{A}_b} = \frac{4f_Rf_L}{f_L^4 - f_R^4}\left[f_R\delta g_L - f_L\delta g_R\right], \tag{10}$$

$$\frac{\delta R_b}{R_b} = \frac{2\,(1-R_b)}{f_L^2+f_R^2}\left[f_R\delta g_R + f_L\delta g_L\right], \tag{11}$$

where $f_R = -\sin^2\theta_W/3$ and $f_L = 1/2 + f_R$ are the tree level couplings of the right and left handed bottom quarks to the Z. The dominant top quark mass dependent one-loop $Zb\bar{b}$ vertex corrections affect only the Z coupling to the left–handed bottom quark, $\delta g_L = -\alpha m_t/16\pi\sin^2\theta_W$. The large difference between the values of f_L and f_R implies that for $\delta g_R = 0$, $\delta R_b/R_b \simeq 11.5\,\delta\mathcal{A}_b/\mathcal{A}_b$. Moreover, the current determination of $\mathcal{A}_b$ at SLC is still subject to large experimental errors[1]

$$\mathcal{A}_b = \begin{cases} 0.841 \pm 0.053 & \text{LEP/SLC global fit;} \\ 0.935, & \text{SM prediction.}\end{cases} \tag{12}$$

Therefore, $\mathcal{A}_b$ does not provide at present any significant constraint on new physics beyond the Standard Model.

2 The MSSM fit to precision electroweak data

The Standard Model global fit to precision electroweak data of Ref. 1 has a χ^2 of 28 for 14 degrees of freedom, which is not a very good fit to the data. Of course, the goodness of fit would improve significantly if the R_c and/or R_b measurements were not correct. On the other hand, it is interesting to examine whether any simple extension of the Standard Model can dramatically alter the predicted values of R_b without seriously affecting the SM predictions for the other electroweak observables.

In general, this is not an easy task. For example, in some models that incorporate new physics beyond the Standard Model, the effects of the new physics on precision electroweak observables do not decouple in the limit where the scale of new physics becomes large compared to m_Z. Such theories predict new non-decoupling contributions to oblique radiative corrections (*i.e.*, corrections to gauge boson propagators), and to vertex corrections such as the $Zb\bar{b}$ vector and axial vector couplings. Fits to the precision electroweak data which allow for new physics contributions to the oblique corrections find no evidence of any such effects.[7] This imposes a strong constraint on any model beyond the SM that attempts to improve the goodness of the SM fit to the precision electroweak data. Typically, the existence of non-decoupling new physics worsens the global fit (although, see Ref. 8 for an example where the global fit is improved).

The minimal supersymmetric extension of the Standard Model (MSSM) is an example of a theory of decoupling new physics. That is, if $M_{\rm SUSY}$ characterizes the scale of supersymmetric particle masses, then the effects of virtual supersymmetric particle exchange to Z decay observables are suppressed by a factor of $m_Z^2/M_{\rm SUSY}^2$. If $M_{\rm SUSY} \gg m_Z$ (but we assume that $M_{\rm SUSY} \lesssim \mathcal{O}(1)$ TeV), then one remnant of the MSSM exists below the scale $M_{\rm SUSY}$—a light CP-even Higgs boson whose mass must be less than $\mathcal{O}(m_Z)$ [see Ref. 9 for an update on the light Higgs mass bound in the MSSM]. It follows that if $M_{\rm SUSY} \gg m_Z$ (calculations[10] show that it is sufficient to have $M_{\rm SUSY} \gtrsim 200$ GeV), then the goodness of the MSSM global fit to precision electroweak data is identical to that of the SM global fit in the case of a light Higgs mass.

If the MSSM global fit is to be better than the SM fit to precision electroweak data, then the MSSM parameters must be such that not all supersymmetric effects have decoupled. In practice, this means that some supersymmetric particle masses must be of $\mathcal{O}(m_Z)$ or less. This is good news for upcoming experimental searches at the LEP-2 and Tevatron colliders. In particular, if the discrepancies between precision electroweak observables and the SM predictions are real and due to the effects of low-energy supersymmetry, then some supersymmetric particles should be discovered during the next few years.

3 Low-energy supersymmetry and R_b

Can parameters of the MSSM be chosen to improve the agreement between theory and observation of R_b, while retaining the success of the SM in describing the body of experimental electroweak data?[11] [Since R_c must be very close to the SM prediction in the MSSM, I shall take the measured value of R_b quoted in eq. (9).] During the past year, models of low-energy supersymmetry have been examined in which R_b is slightly enhanced above the Standard Model prediction.[12,13,14,15] In such models, the global fit to the electroweak data is slightly improved. Note that in order to improve on the Standard Model fit, one must approximately maintain the size of the Standard Model oblique corrections while modifying the $Zb\bar{b}$ interaction. In the MSSM, this is possible if one takes large [small] values of the mass parameters of the scalar super-partners of the left [right] handed top quark, and small values of the Higgs superfield mass parameter μ. Two distinct scenarios emerge depending on the value of the parameter $\tan\beta$, the ratio of the two neutral Higgs field vacuum expectation values. For values of $\tan\beta \sim \mathcal{O}(1)$, the dominant supersymmetric contribution to R_b arises from a one-loop triangle graph containing a light top-squark (dominantly $\widetilde{t}_R$) and a light chargino (dominantly higgsino). For values of $\tan\beta \sim m_t/m_b$, a new MSSM contribution consisting of the triangle graph containing a light CP-odd Higgs boson, A^0, plays a key role. In the latter case, the enhanced Higgs boson coupling to b-quarks when $\tan\beta \gg 1$ is the reason for the enhanced value of R_b.

Although it was initially believed that R_b could be as large as its measured value [eq. (9)] in the MSSM, recent theoretical analyses suggest that this is unlikely. In the MSSM, any physics leading to larger values of R_b also contributes to non-standard top quark decays, such as $t \to \widetilde{t}\widetilde{\chi}^0$ or Based on the absence of light charginos in the most recent LEP run at $\sqrt{s} = 136$ GeV, Ref. 15 quotes an absolute upper limit of $R_b < 0.2174$ in the case of small $\tan\beta$. In the large $\tan\beta$ regime, a rather light A^0 ($m_{A^0} \sim 40$ GeV) and a value of $\tan\beta \gtrsim 50$ is required to generate a large enough R_b. However, in the MSSM, a light A^0 implies a charged Higgs mass near its (approximate) minimum value of m_W (since $m_{H^\pm}^2 \simeq m_W^2 + m_{A^0}^2$). In this case, a recently derived 2σ upper bound,[16] $\tan\beta < 41.6(m_{H^\pm}/m_W)$ is relevant. Moreover, the low m_{A^0}, large $\tan\beta$ regime can be ruled out due to the non-observation of $Z \to b\bar{b}A^0$ at LEP. Ref. 14 concludes that a significantly enhanced R_b in the large $\tan\beta$ regime is ruled out.

I conclude this section with a brief description of a rather unconventional low-energy supersymmetric model that does slightly better in generating an enhanced value for R_b. In the SM, R_b is suppressed relative to its tree-level prediction due to a negative radiative correc-

tions that grows quadratically with m_t. Carena, Wagner and I have constructed a four-generation low-energy supersymmetric model in which $m_t \simeq m_W$. In this model, the effect of the top-quark radiative correction to R_b is reduced. We find that $R_b \simeq 0.2184$, which is within one standard deviation of the measured LEP value [eq. (9)]. Moreover, with this value of R_b, eq. (6) implies $\alpha_s(m_Z) \simeq 0.112 \pm 0.005$, in good agreement with values of $\alpha_s(m_Z)$ extrapolated from lower energy data. Remarkably, such a four-generation model cannot yet be excluded by present data. In our model, $t \to \widetilde{t}\widetilde{\chi}^0$ is the dominant decay, so that top quark decays contain few hard leptons thereby eluding previous searches at hadron colliders. The "top-quark" discovered at the Tevatron is the fourth generation t' quark which decays dominantly into bW^+. Finally, the top quark mass deduced by the global fit of electroweak data can be explained in our model as arising from the sum of oblique radiative corrections generated by the third and fourth generation quarks and squarks. However, such a model will be excluded if no light top squark is discovered in the 1996 LEP-2 run. Further details of this model can be found in Ref. 17.

4 Conclusions

If the anomalies in the R_b and R_c measurements persist, models of low-energy supersymmetry will be hard-pressed to explain the deviation from Standard Model expectations. The discovery of new physics beyond the Standard Model at LEP-2 and/or the Tevatron will be essential for explaining the origin of the discrepancies. On the other hand, if the SM predictions for precision electroweak observables are eventually confirmed, then new physics beyond the Standard Model must (almost certainly) be strongly decoupled at energies of order m_Z. The MSSM with heavy super-partner masses is a model of this type; however, the ultimate confirmation of such a picture will require the detection of supersymmetric particles at future colliders such as the LHC.

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